NACA

RESEARCH MEMORANDUM

INVESTIGATION OF RIM CRACKING IN TURBINE WHEELS WITH WELDED BLADES

By M. B. Millenson and S. S. Manson

Aircraft Engine Research Laboratory
Cleveland, Ohio

TECHNICAL EDITING WAIVED

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
February 12, 1947

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

INVESTIGATION OF RIM CRACKING IN TURBINE WHEELS WITH WELDED BLADES

By M. B. Millenson and S. S. Manson

SUMMARY

The phenomenon of rim cracking in turbine wheels with welded blades is explained on the basis of the occurrence of plastic flow in the rim during the transient starting conditions when thermal compressive stresses resulting from high-temperature gradients exceed the proportional elastic limit of the material. Such plastic flow in compression during the intital operating period results in high-residual tensile stresses, which may cause cracking upon cooling of the turbine. Calculations are presented to show the beneficial effects of shrink-fitting the rim of a composite welded disk on the central portion to decrease the occurrence of rim cracking and of drilling axial holes at a small distance below the rim of the wheel to reduce the propagation of the cracks.

INTRODUCTION

One of the problems in the construction of turbine wheels is the selection of a suitable method of attaching the blades to the turbine disk. Welding the blades to the disk offers the advantages of reduced cost and more rapid fabrication as compared with other methods. Experience in England and the United States in operation of wheels fabricated by welding on the blades, however, has shown frequent occurrence of cracking of the wheel rim between adjacent blades. Typical cracks are shown in figure 1.

An investigation of Type B-31 turbosupercharger wheels reported by the General Electric Company in 1945 shows that rim cracking consistently occurs under repeated cycling through simulated starts and stops. Temperature-cycling experiments on an assembly of Nimonic 80 blades welded to a Stayblade rim were conducted in England at the National Physical Laboratory in 1942. The weld metal abruptly fused with the blade material forming a sharp boundary between the two metals and the suggestion has been made by

British investigators that this boundary might produce a stress concentration leading to intercrystalline cracking. Neither investigation, however, provides any quantitative explanation for the source of tensile stresses that cause the cracking. A possible explanation of these failures and an indication of remedial measures for their prevention based on work done at the NACA Cleveland laboratory are presented.

QUALITATIVE ANALYSIS

From a preliminary analysis, rim cracking in welded turbine wheels appears to be caused by residual tensile stresses occurring in the rim in regions of stress concentration near the blade attachments. These stresses result from a residual strain introduced by plastic flow under compressive stress occurring during starting and initial operating conditions.

When any gas turbine is started, a high temperature gradient is established between the cool center and the hot rim. The differential expansion resulting from the temperature gradient in the various portions of the disk is the predominant factor in producing thermal stresses in the disk. In composite wheels made with a steel center and a heat-resisting alloy rim, an additional effect is caused by the difference in thermal coefficients of expansion of the two materials. Experiments have been conducted on a composite wheel to show the effect of the difference in thermal coefficients of the two materials by measurement of the strains induced when the temperature of the wheel was raised above room temperature. The wheel, instrumented with strain gages as shown in figure 2, was placed in an oven and heated to various uniform temperatures. A plot of a typical set of strain readings converted to stresses is shown in figure 3.

The rim stresses caused by the temperature gradient and increased by the effect of different coefficients of expansion in composite disks with steel centers and heat-resistant alloy rims are compressive and may exceed the proportional elastic limit of the material at the high temperature present near the rim and cause plastic deformation. When the wheel returns to room temperature, the plastic strains that occurred at the high temperatures produce residual stresses. At the rim, these stresses are tensile and if they are high enough, cracks may form in the rim immediately after the wheel is stopped. Ordinarily the stresses are too low, however, to cause cracking in one cycle but will produce some plastic flow in tension. Subsequent cycles of starting and stopping will cause alternate compressive and tensile flow and progressively weaken the material until cracking occurs in a manner somewhat similar to the fatigue of metals under repeated loading.

Because rim cracking is due to residual tension in the rim, cracks are most likely to occur in wheels with welded blades, wheels with inserted blades have discontinuous rims and therefore cannot sustain tensile loading. The effect of compressive flow in discontinuous rims would be loosening of the blades in the mounts. Conceivably, in unusual circumstances the region of compressive flow in such rims might extend below the blade mounts and cause cracks originating in the root of the mounting slot.

The effects of the cyclic plastic flow resulting from cyclic heating and cooling indicate that the number of starts and stops is an important factor in determining turbine-disk life and that steady-state running time has less effect on the length of service.

MATHEMATICAL ANALYSIS

In the course of investigation of stresses in gas-turbine disks, a study has been made of a composite welded wheel. This wheel had an SAE 4340 steel center welded to a Timken 16-25-6 alloy rim at a radius approximately 80 percent of the rim radius. In this investigation two types of computation were made by methods developed at the Cleveland laboratory. The first method, which gives results hereinafter referred to as "the elastic stresses," determines the magnitude of stresses that would be present if the material were at all times linearly elastic. The second method, which gives results hereinafter termed "the plastic stresses," determines the magnitude of stresses present when the material departs from linear elasticity and permanent deformation occurs. This method gives results that represent the actual behavior of the material. The stresses that are computed without consideration of the presence of stress concentration are referred to as "nominal stresses."

The nominal elastic stresses present in the disk investigated under assumed starting conditions of 5300 rpm (70 percent of the rated speed) and a temperature gradient from 70° F at the center to 1050° F at the rim (fig. 4), varying as the tenth power of the radius, is shown in figure 5 together with the corresponding plastic stresses. The plastic flow that occurs under these conditions results in the residual-stress distribution shown in figure 6 in which the plotted values again represent nominal elastic stresses.

Actually, tensile flow would occur at the rim because the room-temperature proportional elastic limit of the Timken alloy is approximately 73,000 pounds per square inch for unstrained metal and would probably be lower after the previous flow in compression. Even if the temperature gradient is considerably less steep than assumed, enough plastic flow will occur to produce serious residual stresses, particularly because the effect of stress concentration has been neglected in these computations.

Calculations are being made to determine the effect of any additional plastic flow that may occur during the time the wheel is warming up to the steady-state running temperature distribution, the effect of cyclic heating and cooling, and the effect of tensile flow after stopping on the residual-stress distribution.

POSSIBLE REMEDIES

One possible method of reducing the high compressive stresses at the rim of a composite wheel such as the one investigated is that of shrinking the rim onto the center before welding and thereby introducing initial tension in the rim. The elastic tangential-stress distribution in several such wheels with various amounts of shrink fit under assumed starting conditions is shown in figure 7. Shrinking the rim on the center section has a marked effect on the compressive rim stresses; however, tensile stresses will be induced at the rim when the disk is at room temperature and excessive tensile stresses will result at the juncture of the two materials. Consideration of figure 7 and of calculations of room-temperature stresses indicates that a diametric interference of 0.075 inch is a satisfactory value. This amount of shrink corresponds to a temperature difference of 400° F if the center part is kept near room temperature for the materials in the disk investigated. If the shrinking operation is carried out with the center at a higher temperature, this amount of interference can be obtained with a smaller temperature difference because of the variation of the coefficient of thermal expansion with temperature. Although the use of this shrink would not lower the starting stresses below the proportional limit of the material at the rim, it would reduce the amount of flow during operation to about one-half that occurring in a wheel with no shrink and thereby produce a corresponding reduction in residual stresses. Calculations indicate that change in the location of the weld has little effect on the magnitude of the rim stresses.

Another possible solution to the problem is to slot the wheel between blades to a depth of approximately one-half inch with a stress-relief hole at the base of the slot. Slotting would reduce the effective diameter of the wheel and the residual stresses that occur would hence be lower than in the unslotted disk. The elastic and plastic tangential-stress distributions that would be present in the slotted disk during the starting period are shown in figure 8. The resulting elastic tangential residual stress is presented in figure 9. The stress at the effective rim of the disk is lower than in the unslotted disk and has been removed from the junction of blade and weld metal, the region that is indicated as critical by British investigators, to the region containing a stress-relieved hole.

Drilling holes on the same wheel radius as the relief holes but omitting the slots would allow cracks to progress into the holes and have essentially the same effect as the slots. Although slots have the advantage of preventing the crack from taking an arbitrary path and possibly missing a hole, use of holes alone would permit easier wheel fabrication and the irregular surface of the crack might also provide friction damping in the event of blade vibration.

SUMMARY OF RESULTS

A principal difficulty encountered in the fabrication of turbine wheels with welded blade assemblies has been the frequent occurrence of rim-cracking. From work completed in the study of such wheels, these failures appear to be caused by high residual tensile stresses in the rim that occur as a result of compressive flow during turbine operation. Slotting and drilling the disk rim and correctly designing the amount of shrink fit are suggested as possible remedies.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

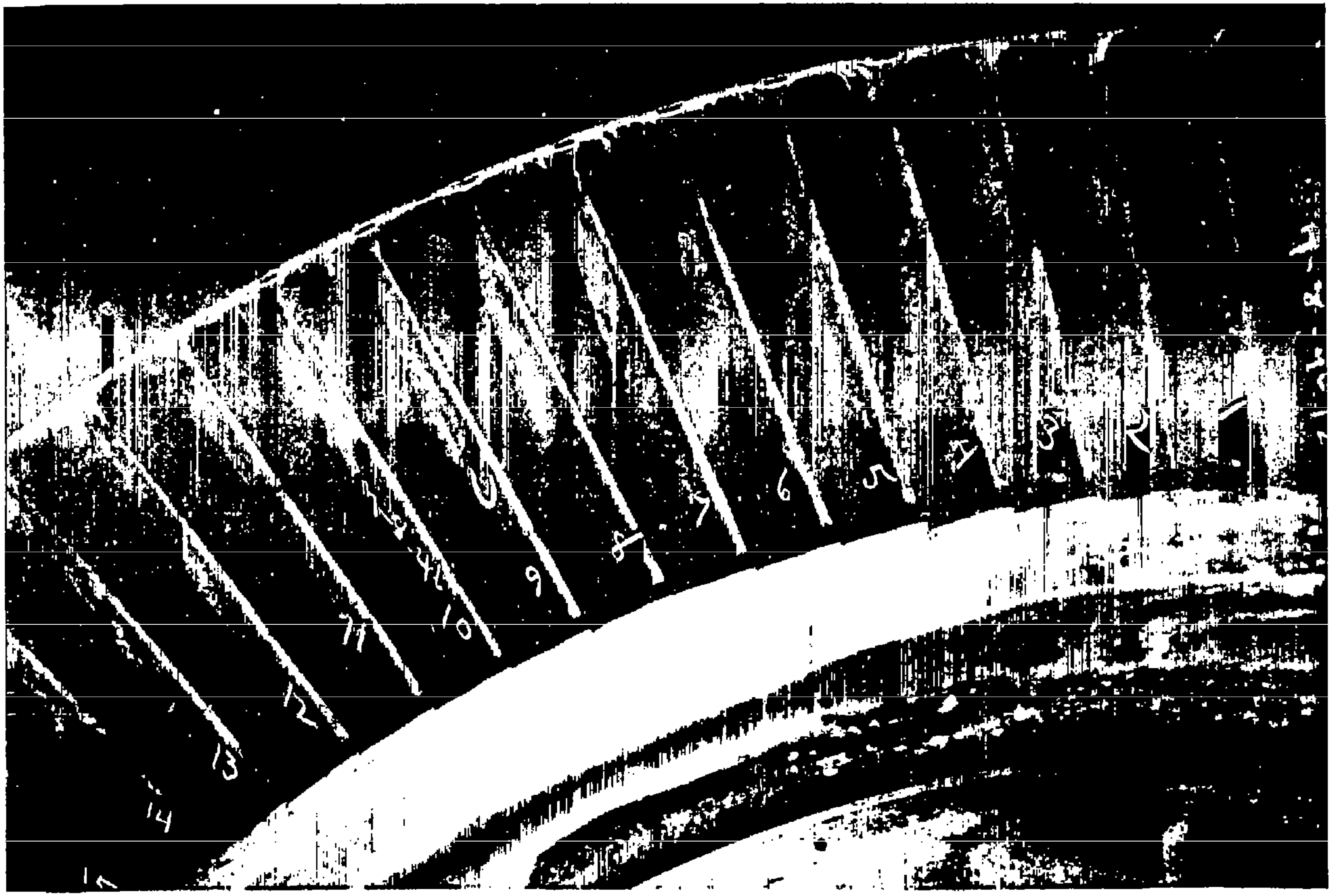

Figure 1. - Typical interblade cracks at rim of turbine wheel with welded buckets.

NACA
C-15274
7-8-46

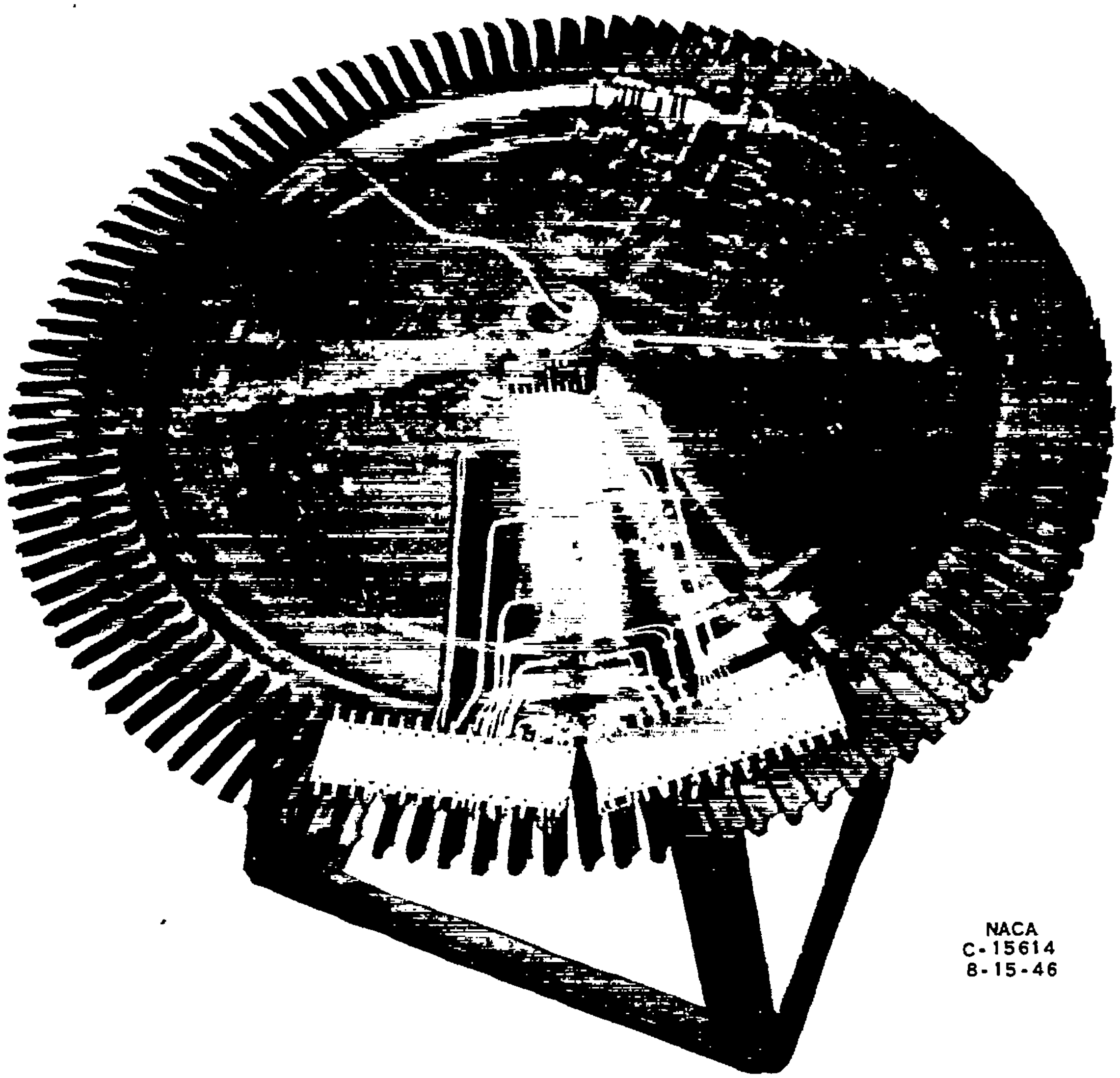

Figure 2. - Strain-gage installation on composite welded turbine wheel to measure thermal stresses in composite disk due to difference in coefficient of thermal expansion between steel central portion and high-temperature alloy rim.

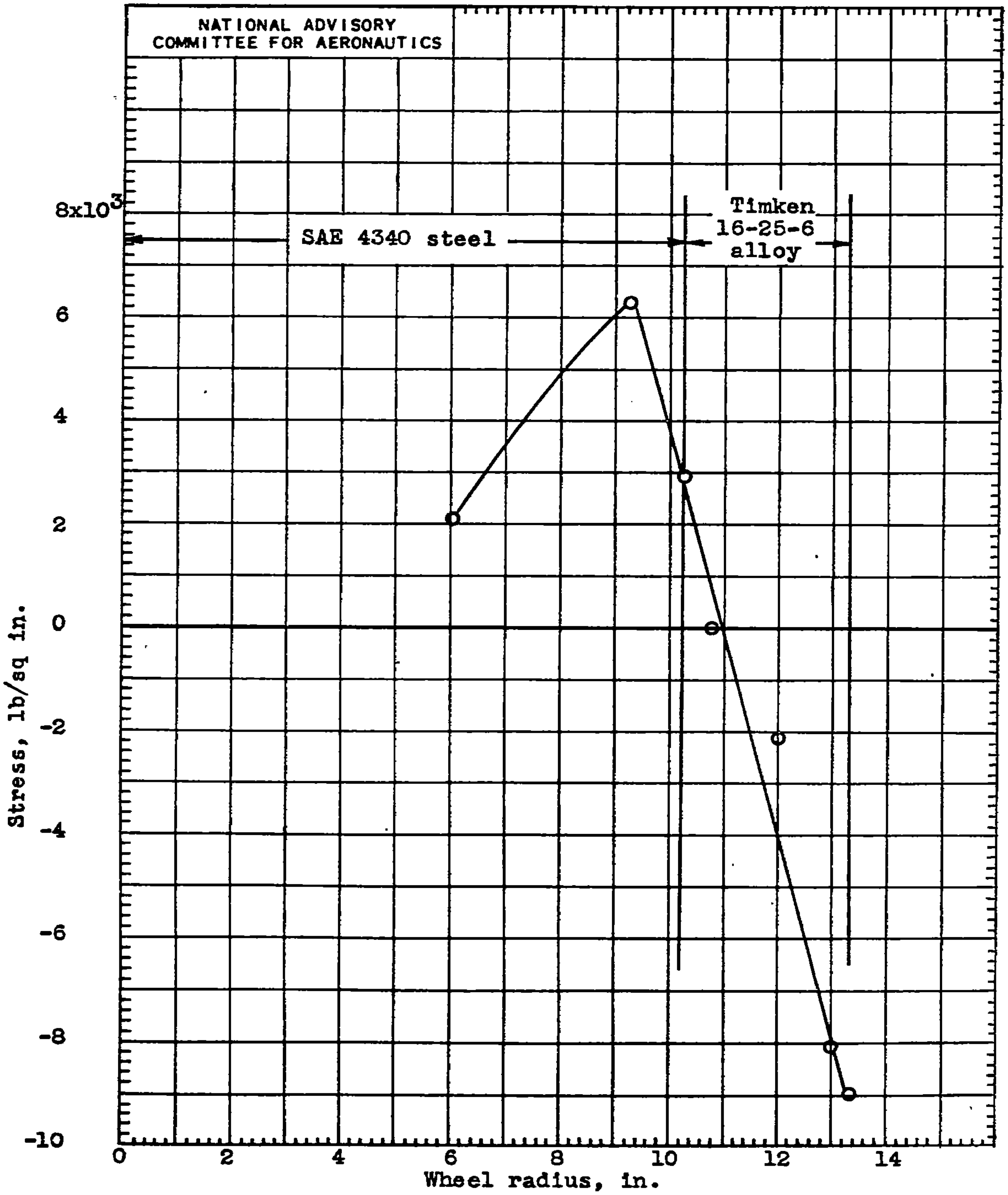

Figure 3. - Tangential stress distribution obtained from strain-gage data on composite welded wheel at rest at temperature of 230° F.

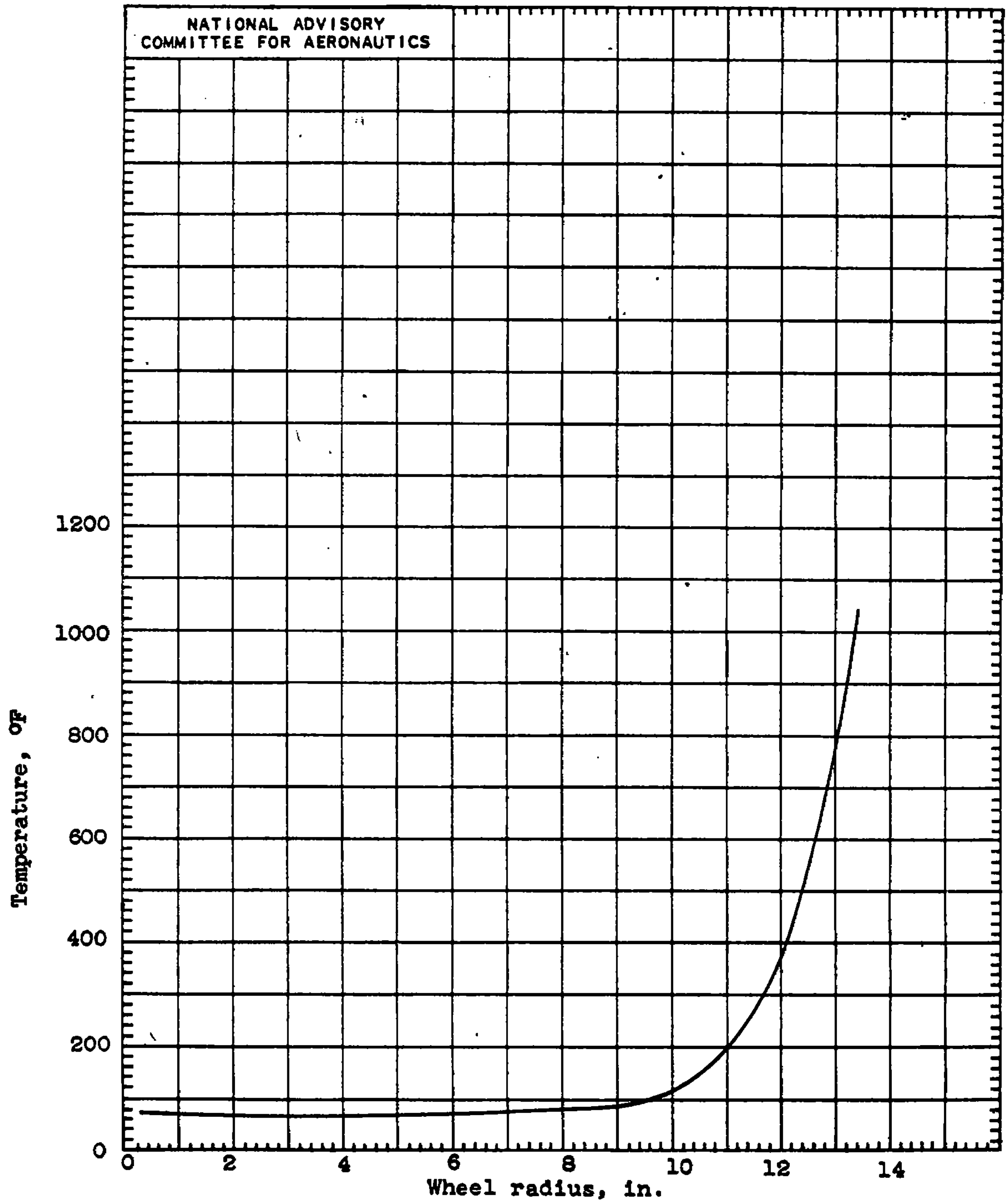

Figure 4. - Assumed temperature distribution in composite welded wheel during starting period.

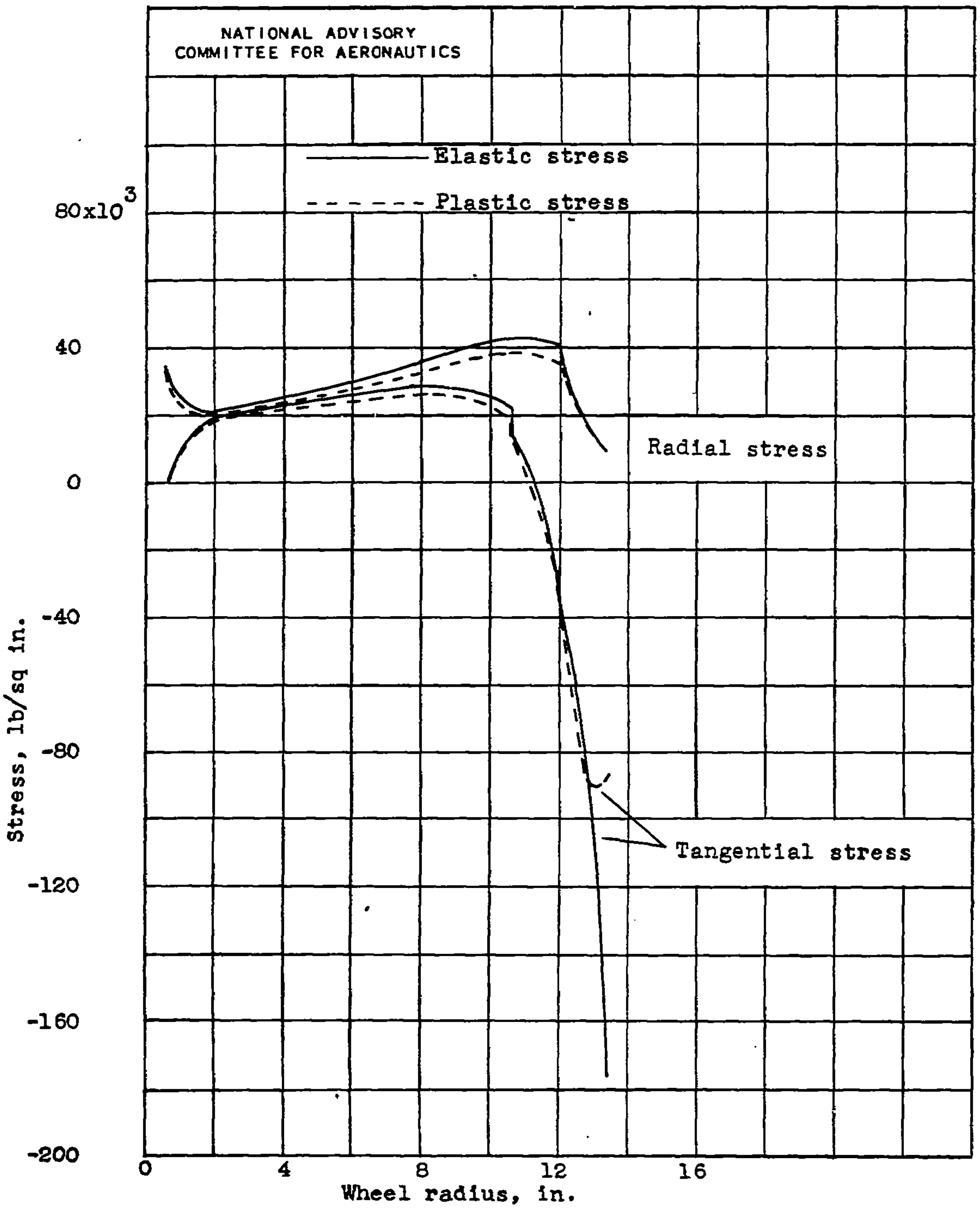

Figure 5. - Computed nominal stresses in composite welded wheel during starting period.

697

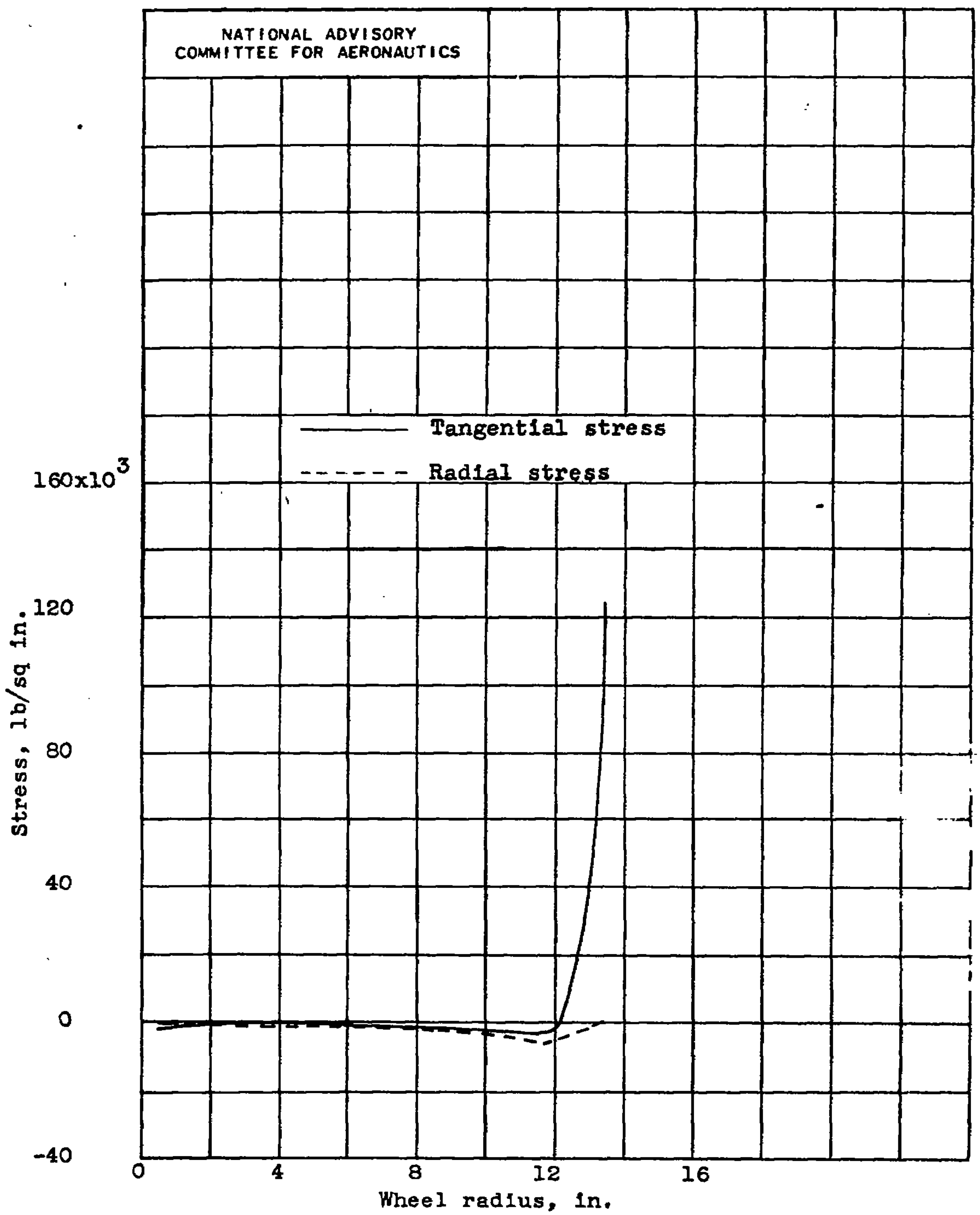

Figure 6. - Computed elastic residual stresses in composite welded wheel due to plastic flow during starting period.

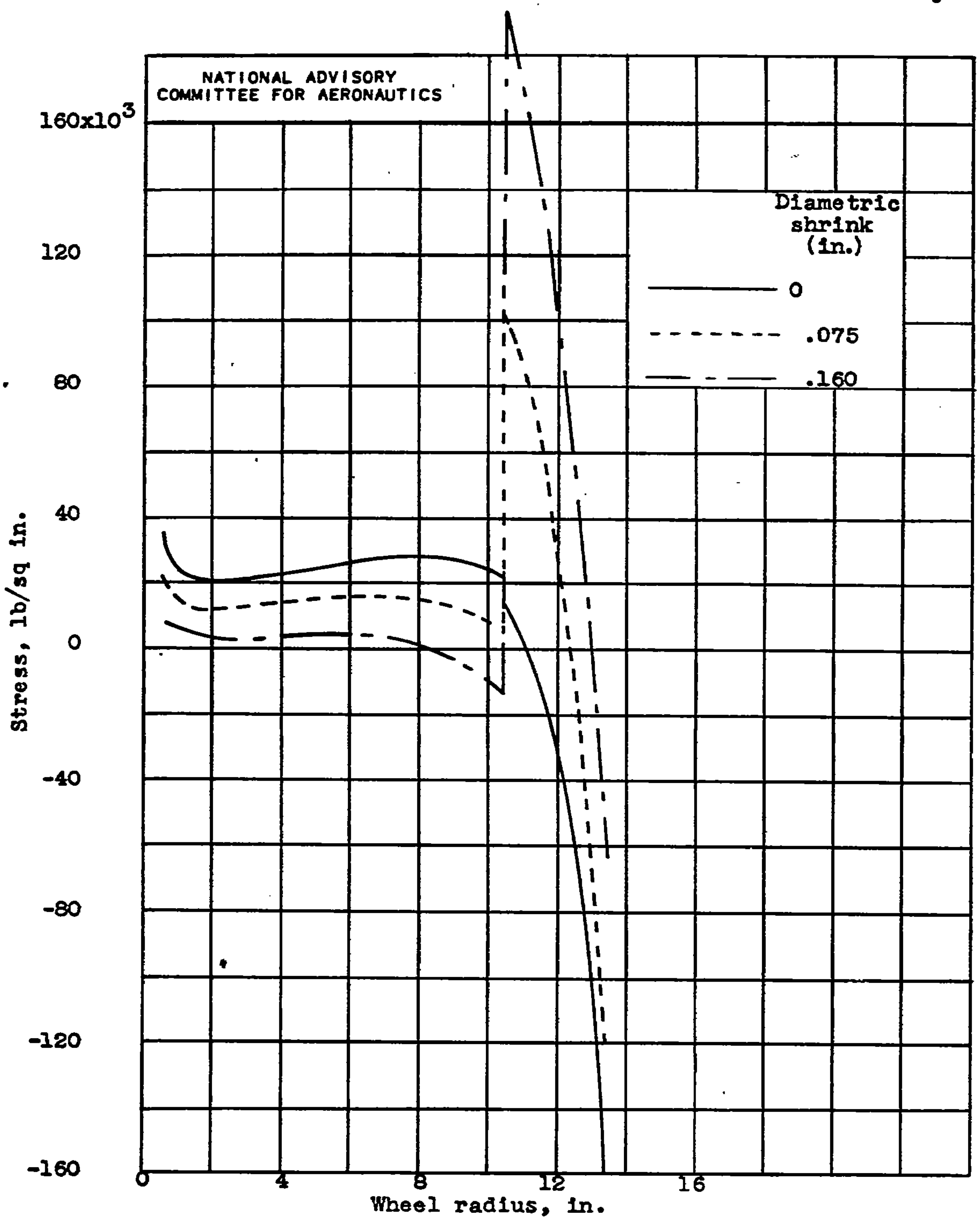

Figure 7. - Computed nominal elastic tangential stresses in composite welded wheels with several amounts of shrink fit during starting period.

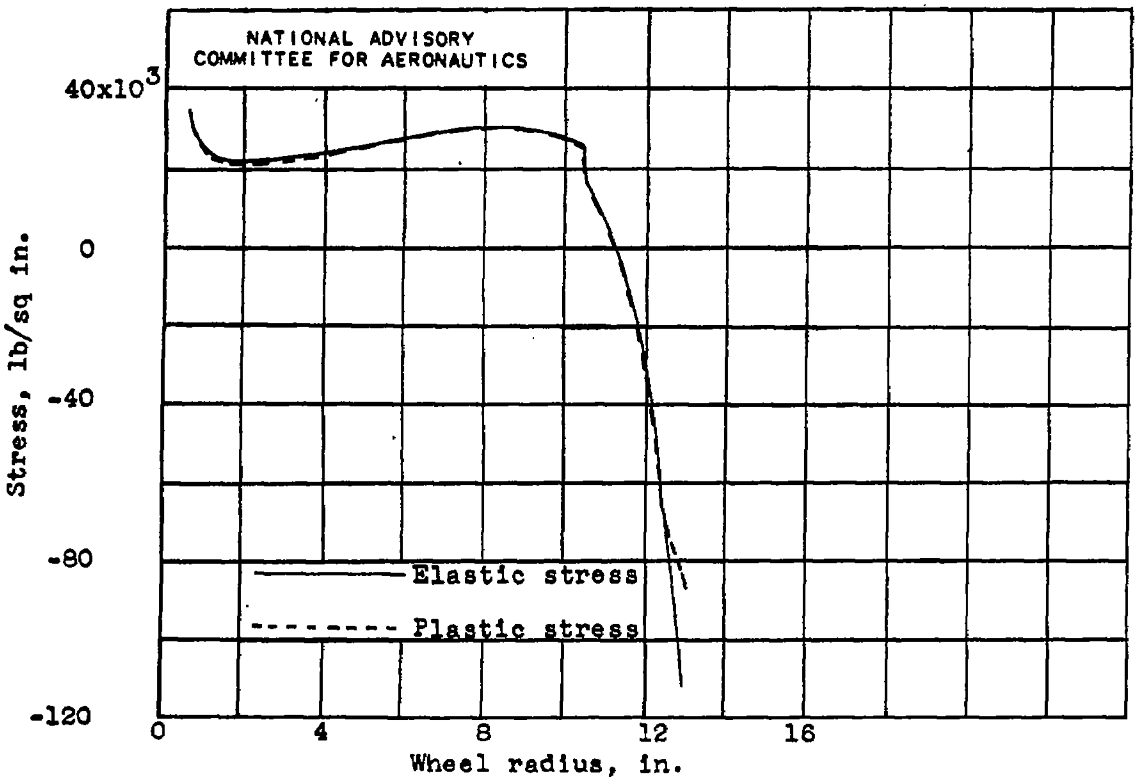

Figure 8. - Computed nominal tangential stresses in slotted composite welded wheel during starting period.

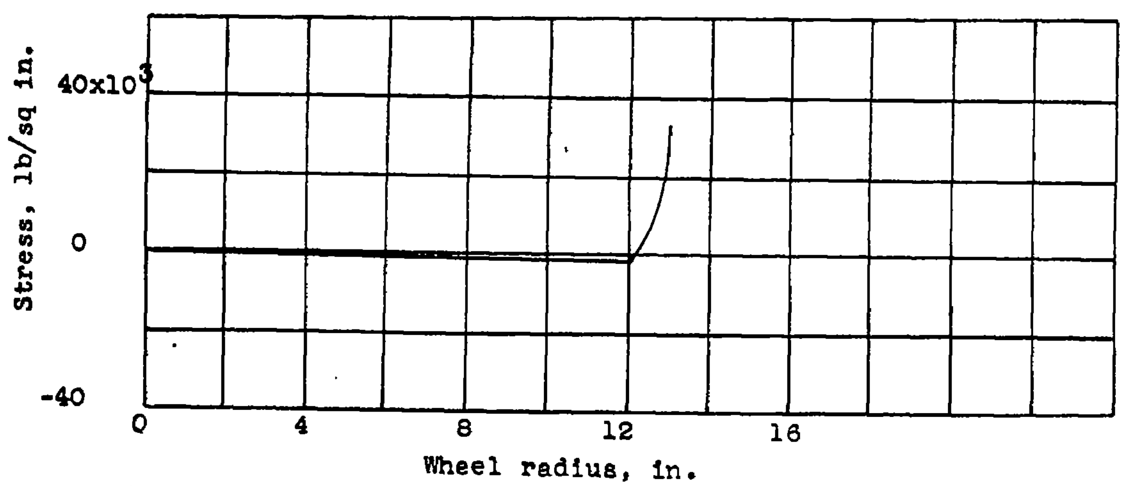

Figure 9. - Computed nominal tangential residual stress due to plastic flow at start in slotted composite disk.